High Performance Position Control of Double Sided Air Core Linear Brushless DC Motor

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Abstract

Double-Sided Air Core Linear Brushless DC motors widely used in the industry where longitude motion is needed. In terms of efficiency, high speed and acceleration, long life, Stiffness, few moving parts, precise positioning and no transmission components, and so on have many advantages. In this paper position control of a Double Sided Air Core Linear BLDC motor is studied by two methods, first of all the classical PID control method is applied to the system and then Fuzzy-PID control method is investigated on system. The motor specifications and technical features of it are derived and presented. The simulation and the motor model including the control algorithm is built by using of Simulink and is investigated. Finally, to validate simulation result, designed controllers are applied to the Double-Sided Air Core Linear Brushless DC Motor practically. The experimental test results validate simulation result and the accuracy of the both control method and their dynamic performances are compared with each other.

1. Introduction

In recent years, Brushless Direct Current (BLDC) motors have achieved rapid popularity. Generally, BLDC motors are used in industries such as appliances, automotive, consumer, medical, industrial automation equipment and instrumentation. Moreover, they are more reliable and can be used in poor environmental conditions [1, 2]. Unlike brushed motors, these motors have no chance of sparking. Thus it makes them better suited to environments with volatile chemicals and fuels. In a brush DC motor, the motor assembly contains a physical commutator which is moved by means of actual brushes in order to move the movable armature. In contrast, in BLDC motor, electrical current powers a permanent magnet is caused to motor motion, therefore no physical commutator is necessary. While brushless DC electric motor known as electronically commutated motors and it is categorized as a synchronous motor that is powered by a DC electric source via an integrated inverter or switching power supply, which produces an AC electric signal to drive the motor.

In this study, Linear BLDC motors are considered which their controllability have crucial role in industry today. According to that Linear Brushless DC motor control is one of the important research topics which are studied as position controlling, speed controlling and etc. Furthermore, Linear Brushless DC motors are beneficial because of their direct drive, zero backlash for higher accuracy, Non-contact, non-wearing for enhanced reliability, high acceleration and velocity reduces cycle times, low maintenance and long life lowers cost of ownership [1, 2]. Today in industry applications, Linear BLDC motors are made with different structures, these can be moving-magnet and moving-coil motors. In this paper the moving-coil type is considered.

This study is demonstrated an approach of classical PID and Fuzzy-PID control methods for high precision position control of Linear Brushless DC motor to enhancement and consideration of control methods. First, the classical Proportional Integral Derivative (PID) controller is considered which is accepted and used between one the most universal controller in industry sector. However, the PID controller has a powerful performance, although there are some insufficiency such as optimal tuning issues and adjustment difficulty in non-linear system states. As a second method, Fuzzy-PID controller which is accepted as a capable method on controlling nonlinear systems while it is used the human operator knowledge plus the PID controller benefits. Fuzzy controller is used independent system parameters and it is made a suggestive benefit to classical PID controller. Although, response of Fuzzy controller is considered as a deterministic system is so delicate to the distribution of membership function, but its computation time is longer than PID controllers. By consideration of these advantages, this paper is investigated fuzzy-PID control strategy – which is combination of both.

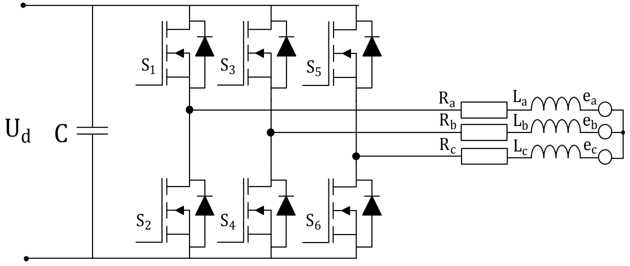

Fig. 1. Power circuit and motor schematic

2. The Mathematical Model of Linear BLDC Motor

The Linear Brushless DC motor has inductive trapezoidal Electromotive force waveform and nonlinear mutual inductance between windings. Nonetheless the motor is operated within the rated condition and the saturation effect due to current level is neglected and iron losses are negligible. Moreover, It is assumed the three-phase stator windings are symmetrical star connection and parameters are constant [3, 4]. In addition, stator resistance and inductance of each winding are assumed equal and self and mutual inductances are presumed constant. The Linear Brushless DC motor each phase voltage equation is written as below;

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \begin{bmatrix} V_N \\ V_N \\ V_N \end{bmatrix} \quad (1)$$

Where V_a, V_b and V_c are voltages of stator winding of each phase, R_a, R_a and R_c are the resistance of each phase winding, i_a, i_b, i_c are each phase winding's current, e_a, e_b, e_c is the reversed electromotive force of each phase winding, L is difference in self-inductance of each phase and mutual inductance between every two phase winding, V_N is the neutral voltage. Under abovementioned assumptions plus presuming that: $i_a + i_b + i_c = 0$, and moreover considering mutual inductance of concentrated winding configuration is negligibly small. Based on all these assumptions, the Linear BLDC motor can be represented as:

$$u_a - u_0 = R.i_a + L\frac{d}{dt}i_a + e_a \tag{2}$$

$$u_b - u_0 = R.i_b + L\frac{d}{dt}i_b + e_b \tag{3}$$

$$u_c - u_0 = R.i_c + L\frac{d}{dt}i_c + e_c \tag{4}$$

Where: u_a, u_b, u_c - phase winding voltages; u_o- differential voltage between the central point of the star connection of motor winding and the power stage natural zero, so R resistance of each phase; i_a, i_b and i_c- phase currents; L - self-inductance of each phase; e_A, e_B, e_C - trapezoidal shaped Back-EMFs. Therefore, the voltage in the central point of the star connection of motor winding is as follows:

$$u_0 = \frac{1}{3}\sum_{j=a,b,c} u_j - \sum_{j=a,b,c} e_j \tag{5}$$

In an ideal situation in Linear Brushless DC motors, only a two-phase winding are on conduction when it is operating at 120 electrical angle conduction mode. So the electromagnetic force equation of Linear Brushless DC motor can be shown as below:

$$F_e = (e_a i_a + e_b i_b + e_c i_c)/v \tag{6}$$

Where v is the linear velocity of the stator on double-sided air core Linear Brushless DC motor, while the moving part is put windings in its chamber as stator, the interaction of F_e with the load force determines how the motor speed builds up:

$$m\frac{dv}{dt} = F_e - F_{load} - D.v \tag{7}$$

Where: F_{load} - load force; m - mass; D - damping coefficient; v - velocity.

Below is the mathematical formulation that describes the motor dynamics. The formula is similar to a rotational motor equation and can be written in the following way:

$$F_m = m\frac{dv}{dt} + F_{load} + D.v \tag{8}$$

The dynamic equation states that the force acting on the moving part unit includes an effect due to mass, a frictional component and the force corresponding to a mechanical load driven by the motor (F_{Load}).

According to electrical equations, the fundamental formulation of the linear BLDC motor is set of equations which are explained above, constitutes a model of the DC motor, which may be defined as a nonlinear system. The main restrictions of this model which below assumptions are found a solution for them, with respect to a real motor are;

- That the magnetic circuit is linear.
- And the mechanical friction is only linear section in the motor speed operation; namely, only viscous friction is assumed to be present in the motor.

Since the relationship between the force and the current is given by the following equation:

$$F_e = k.\emptyset.i \tag{9}$$

Consequently, the output force is difference between electrical force and the pull-out force.

$$F_{out} = F_e - F_{pull-out} \tag{10}$$

According to experimental test, the nominal friction of motor and the pull-out force are measured to be 5N and 5.6N, respectively. Also experimental test are started from 10A, the $k\emptyset$ values are calculated for each current-force result pair. The average value of the $k\emptyset$'s from the 10 results were calculated again, thus the average value of $k\emptyset$ is taken 8.48. Besides that, the reversed electro-motive force of each phase windings can be considered as below.

$$E = vBl\,sin\,\theta \tag{11}$$

As known from Faraday law, the velocity is perpendicular to the magnetic field (which is made by magnets) so the generated back EMF is;

$$E = vBl \tag{12}$$

Where B is the flux density (field strength), l conductor length and v coil or stator velocity, above equation shows that the electromotive force of motor is proportional to motor speed when the motor flux constant. According to electromagnetic force equation, Linear Brushless DC motor electromagnetic force is relative to the currents which pass through the phase winding and the velocity too.

Table 1. Motor characteristics

Parameters	***Values***
Supply voltage	24 V
Max. Moving Force	163.8 N
Calculated Max. Moving Force	161.2 N
Max. Rated speed	6.7 m/s
Max. Rated current	20 A
No load current	2.64 A
Resistance of each coil	0.301 Ω
Inductance of each coil	140.2 mH
Force constant	8.48 N/
Moving mass	0.51 kg
Motor length	0.3 m

The Linear BLDC motor is fed with the inverter which is connected to the Linear BLDC motor. Power circuit and motor schematic are demonstrated in Fig. 1 for further investigation. In addition to that, with the above equations the obtained mathematical model is simulated using Simulink and the block diagram of the Linear BLDC motor is shown in Fig. 2.

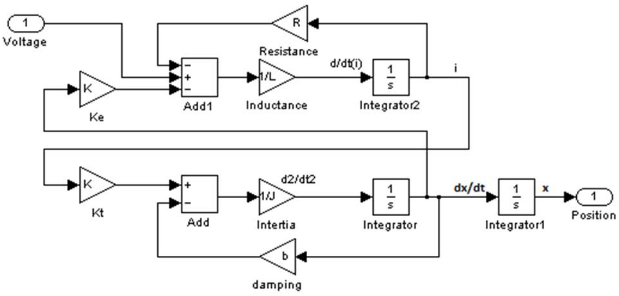

Fig. 2. Block diagram of Linear BLDC Motor

As a result, transfer function of the Linear BLDC motor in frequency domain is given by:

$$\frac{v(s)}{V(s)} = \frac{sx(s)}{V(s)} \tag{13}$$
$$= \frac{k_t}{JL\left(s^2 + \left(\frac{J.R + B.L}{J.L}\right)s + \left(\frac{B.R + K_t.K_e}{J.L}\right)\right)}$$

V is represent velocity, x position, and V is voltage of each phase, J Moment of inertia of motor and load in Kgm^2/rad, B frictional constant of motor and load in $N.m/(rad/sec)$, K_e= back-EMF constant in $Volt/(rad/sec)$, K=Force constant in N/Ampere, R Stator resistance of each phase in ohms and the L Stator inductance of each phase in Henry.

3. Position Controller

Driver circuit of three phase power convertor of Linear BLDC motor contains six switches to energize two Linear BLDC motor phases simultaneously. Therefore, the stator position that rules the switching sequence of the power switches and it is determined by three Hall sensors which are mounted on the stator structure. So, back EMF status and switch states in each mode is shown in Table 2. BLDC motor control methods are specifically determined switching condition in different states to control motor position, speed and current [5, 6].

Table 2. Hall sensors, Back EMF status and switch states

Hall-a	***Hall-b***	***Hall-c***	***Emf A***	***Emf B***	***Emf C***	***Q1***	***Q2***	***Q3***	***Q4***	***Q5***	***Q6***
0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	-1	1	0	0	0	1	1	0
0	1	0	-1	1	0	0	1	1	0	0	0
0	1	1	-1	0	1	0	1	0	0	1	0
1	0	0	1	0	-1	1	0	0	0	0	1
1	0	1	1	-1	0	1	0	0	1	0	0
1	1	0	0	1	-1	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0	0	0	0

3.1. Classical Controller

PID (Proportional-Integral-Derivative) control is one of the prior control methods which are used in industrial applications widely. Also it is called classical control that its typical control block diagrams is shown Fig. 3.

In this control method, the error signal $e(t)$ is needed to generate controlling signal which is proportional to error value, with the resulting signals weighted and summed to form the control signal $u(t)$ applied to the plant model. So mathematical description of the PID controller is shown as below:

$$u(t) = K_p\left[e(\tau) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(\tau)}{d\tau}\right] \tag{14}$$

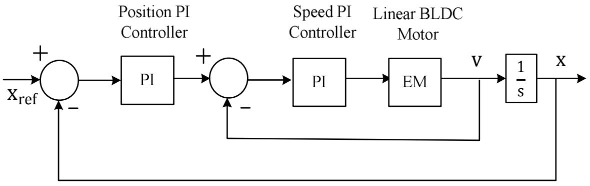

Fig. 3. Typical block diagram of PID controller

Where $u(t)$ is the input signal to the system model which in this study is Linear BLDC motor model, the error signal $e(t)$ is defined as a $e(t) = u(t) - x(t)$, and $x_{ref}(t)$ is the reference input signal which is given by user to the system or is selected according to system condition to have next step in a system process. In this system, the behavior of the PID controller is determined by K_p , T_i , T_d values [8, 9]. That can be tuned by Ziegler-Nichols tuning formula that obtained when the plant model is given the step input. In this study, Frequency response is chosen to design PID controller, according to Ziegler-Nichols tuning method.

3.2. Fuzzy-PID Controller

Since motor drive system is nonlinear and parameters variations are natural, using nonlinear controller is needed to modify entire performance of the motor drive system. As it is known, Fuzzy method simulates human thinking way for nonlinear structures, which usually mathematical models cannot be effective and efficient [10, 11].

Moreover, the classical PID controller is not so efficient to adjust the controller parameters specifically it is not qualified in real time control parameter's adjustment in spite of that the Fuzzy-PID controller method which is designed and investigated in this paper improve performance of controller system with its capability.

In the Fuzzy-PID controller system, the Fuzzy controller section, control PID controller parameters to have the best response to system fluctuations [12, 13, 14]. According to detection of error signal and parameters variation in the system, fuzzy controller determined optimum parameters for PID controller coefficients. Table 3 illustrate the Fuzzy-PID controller decision concept, the deviation signals and correspond fuzzification condition to determination of PID controller parameters between fuzzy relations. The error signal is 10 bits of data in its maximum rate, so it is between [-1024,1024] interval. In this study error signal domain is separated to 7 phases: (0,8), (8,16), (16,32), (32,64), (64,128), (128,256), (256,1024) and according to error sign the control determined the motion direction. Therefore, PID controller parameters adjusted according to systems errors in specific instant which is cause to have more dynamic drive system controller.

Fuzzy sets is described such as; So Big (SB), Big (B), Big Medium (BM), Medium (M), Medium Small(MS), Small (S), So Small (SS) the fuzzy rules are assigned in Table 3. According to error states the fuzzy system determine K_p, K_i and K_d parameters values.

Table 3. Fuzzy-PID Controller Rules of K_p ,K_i , K_d

PID Parameters	*Error Signal* ***e***							
		SB	*B*	*BM*	*M*	*MS*	*S*	*SS*
$\frac{de}{dt}$	*SB*	SB	SB	B	B	BM	M	M
	B	SB	SB	B	B	M	M	MS
	BM	B	B	B	M	M	M	MS
	M	B	B	M	M	MS	MS	S
	MS	BM	M	M	MS	MS	S	S
	S	M	M	M	MS	S	SS	SS
	SS	M	MS	MS	S	S	SS	SS

Fuzzy-PID controller with error and differential error which are as inputs and PID parameters (K_p ,K_i , K_d) as outputs of controller. Error and differential of error can satisfy the tuning of the PID parameters dynamically. Using the fuzzy control rules to modify the PID parameters online it assists to have proficient controller, where we constitute a Fuzzy-PID controller, the structure of Fuzzy-PID controller block diagram is shown in Fig.4

Where $e(t)$ is error and $\frac{de}{dt}$ error changes rate.

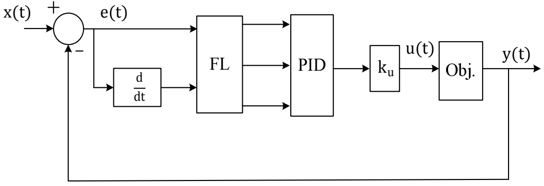

Fig. 4. Block diagram of Fuzzy-PID control system

4. Simulation and Experimental Results

In this study, the control system simulations are performed by Simulink. According to Linear BLDC motor characteristic and parameters, the Double Sided Air Core Linear BLDC motor mathematical model is performed in Simulink. As it is shown in Fig. 5 and 6 the simulation results are presented in two tests. The classical PID controller and Fuzzy-PID controller performance are demonstrated which are stable. In spite of that it has been desired to have current control and speed control in the system, to have more controllable, more accurate, applicable and faster system. Therefore, the results can be improved by using inner current and speed control loops.

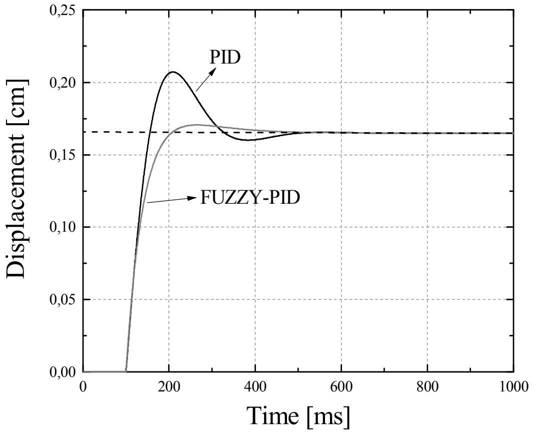

Fig. 5. System's response to PID and Fuzzy-PID position controllers (experiment 1)

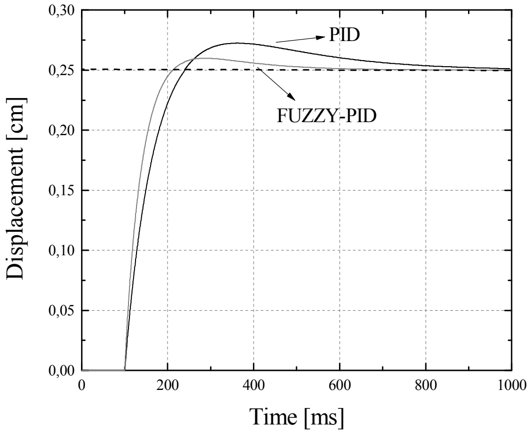

Fig. 6. System's response to PID and Fuzzy-PID position controllers (experiment 2)

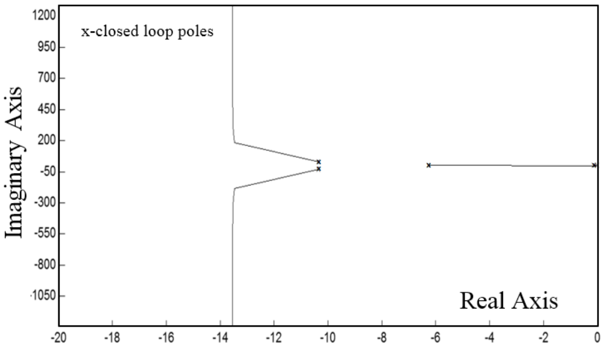

Fig. 7. System root locus diagram

Afterward performance of classical PID controller and Fuzzy-PID controller of Double Sided Air Core Linear BLDC motor on different reference points are tested practically too.

All experiments are conducted at the ITU Power Electronic Laboratory and Mekatro R&D Company.

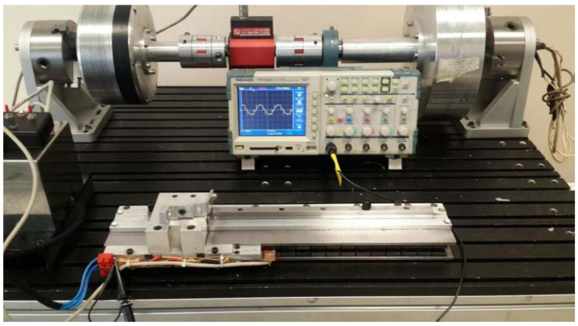

Fig. 8. Motor test bench

The tests are performed with different strategies to get the various performance of controllers, therefore mechanical load is applied to the motor during the experiments, 98 N (10 kg). Fig. 9, 10 and 11 is shown three test results with classical controller, each time from set point (x=0) to a different positions, such as long distance, medium distance and short distance, to ensure measurement of motor precision position control.

For further investigations, Fuzzy-PID controller is applied to the system and its performance on Linear BLDC motor from different reference points are considered and the test results are shown in Fig. 12, 13 and 14. The same mechanical load is applied to the motor during the tests, 98 N (10 kg).

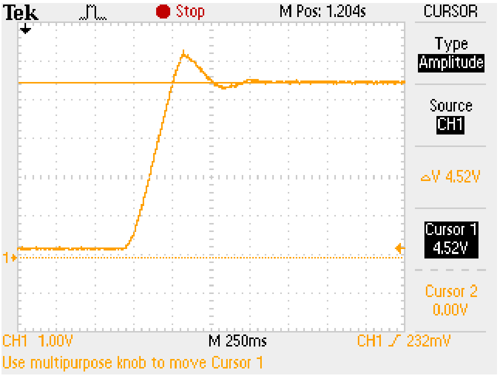

Fig. 9. Classical position controller test result for long distance (x = 0 to x = 268 mm).

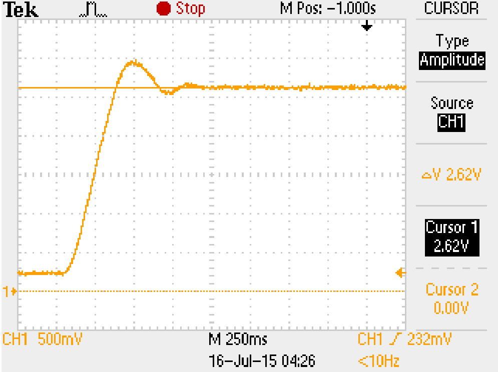

Fig. 10. Classical position controller test result for medium distance (x = 0 to x = 153 mm)

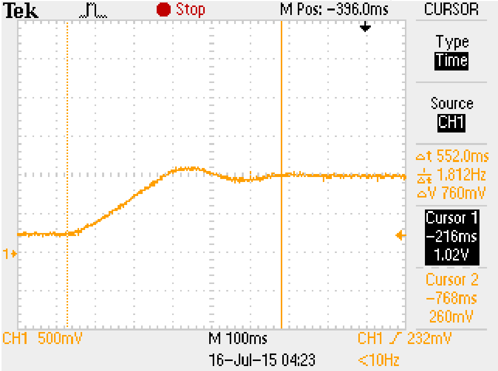

Fig. 11. Classical position controller test result for short distance (x = 0 to x = 58.1 mm)

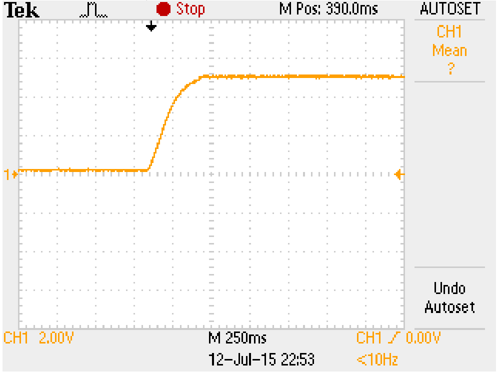

Fig. 12. Fuzzy-PID position controller test result for long distance (x = 0 to x = 268 mm)

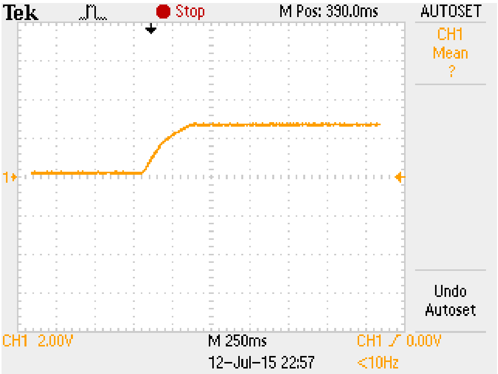

Fig. 13. Fuzzy-PID position controller test result for medium distance (x = 0 to x = 153 mm).

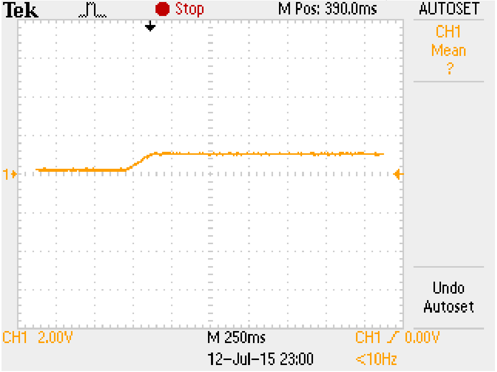

Fig. 14. Fuzzy-PID position controller test result for short distance (x = 0 to x = 58.1 mm)

Comparison between practical test results is clarified that in the classical PID controller performance, average overshoot is about 10%, the settling time is approximately 800ms, rising time is about 300ms and maximum steady state error is 288 microns. On the other hand, as it can be seen from Fuzzy-PID controller results, the dynamic performance of position controller is improved significantly. In total, the response time of controller is shortened, overshoot is reduced to 2.5% and it has a better robustness when load is applied. Furthermore, the control system settling time is reduced to around 350ms, rising time is about 260ms and maximum steady state error is 288 microns.

5. Conclusions

In this paper, the PID and Fuzzy-PID control techniques are successfully implemented for the Double Sided Air Core Linear BLDC motor drive system. The performance of both in different conditions are investigated on Linear BLDC drive system with experimental tests. Finally, tests are proved the simulations result. According to experimental results, as it has been shown in the Fuzzy-PID controller performance compare to classical PID controller results, the dynamic performance of position controller is improved significantly and the response time of controller is shortened. It is demonstrated that Fuzzy-PID controller on Linear BLDC have better performance under load condition in the system. Next to that the experimental results clearly show that Fuzzy-PID controller on Linear BLDC drive can provide an improved response with better rise time, and settling time when the motor is subjected to load. Overall, Fuzzy-PID controller has better performance compare to classical PID controller therefore it is preferred for automation, robotics, and high precision position control systems.

7. References

[1] J. Lu, X. Zhang, S. Tan, X. Guan, W. Ma and Sh. Song, “Research on a Linear Permanent Magnet Brushless DC Motor for Electromagnetic Catapult”, IEEE TRANS. on plasma science, vol. 43, no. 6, june 2015.

[2] H. Gurol, “General Atomics linear motor applications: Moving towards deployment,” Proc. IEEE, vol. 97, no. 11, pp. 1864–1871, Nov. 2009.

[3] Tibor. B., Fedak. V., Durovsky. F., “Modeling and simulation of the BLDC motor in MATLAB GUI,” Industrial Electronic (ISIE), 2011 IEEE International Symposium on, pp.1403-1407, 2011.

[4] P. Pillay and R. Krishnan, “Modeling, simulation, and analysis of permanent-magnet motor drives, part ii: The brushless dc motor drive,” IEEE Trans. Ind. Appl., vol. 25, no. 2, pp. 274–279, Mar./Apr. 1989.

[5] Alaeinovin, P., Jatskevich, J., “Hall-Sensor Signals Filtering for Improved Operation of Brushless DC Motors,” Industrial Electronics Society, IEEE International Syposium, pp.613-618, June. 2011.

[6] Yong-Kai Lin, Yen-Shin Lai, “Pulse width Modulation Technique for BLDCM Drives to Reduce Commutation Torque Ripple Without Calculation of Commutation Time,” Industry Applications, IEEE Transactions on Volume 47, pp. 1786-1793, 2011.

[7] R. Shanmugasundram, K. M. Zakariah, and N. Yadaiah, “Low-cost high performance brushless dc motor drive for speed control applications,” in Proc. IEEE Int. Conf. Adv. Recent Technol. Commun. Comput, Kottayam, India, Oct. 27–28, 2009, pp. 456–460.

[8] K. Ang, G. Chong, and Y. Li, "PID control system analysis, design, and technology," IEEE Trans.Control System Technology, vol. 13, pp. 559-576, July 2005.

[9] Q.Wang, T. Lee, H. Fung, Q. Bi, and Y. Zhang, “PID tuning for improved performance,” IEEE Trans. Contr. Syst. Technol., vol. 7, no. 4, pp. 457–465, Jul. 1999.

[10] Zdenko Kovaccic and Stjepan Bogdan, “Fuzzy Controller design Theory and Applications”, © 2006 by Taylor & Francis Group. International, 2002.

[11] Guangqi Zeng, Junan Hu, Dong Wang, etc. Fuzzy Control Theory and Engineering Application [M]. Hua Zhong University Press, 2006, 8.

[12] Jinjin He, Zhiqin He. Research of Brushless DC Motor Control Based on Fuzzy PID Algorithm [J]. Machinery & Electronics, 2010, 7(1):80-82.

[13] Wei Xu,Baida Qu,Baoguo Xu.The Speed Control of Brushless DC motor Based on Fuzzy PID Model[J]. Electrical Technology, 2010, 10(11):7926-7929.

[14] Rubai. A, Marcel J, Castro. S, Abdul R.O, “Design and Implementation of Parallel Fuzzy PID Controller for High-Performance Brushless Motor Drives: An Integrated Environment for Rapid Control Prototyping” IEEE Transactions on Industry Applications, Vol. 44, No. 4, July/ August 2008.